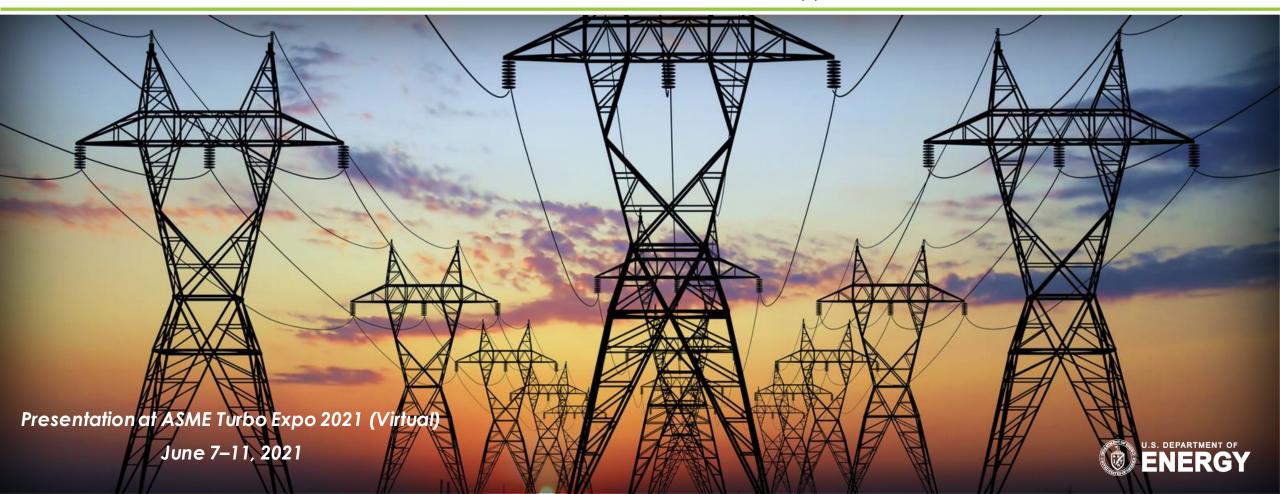
Optimized Performance and Cost Potential for Indirect Supercritical CO₂ Coal Fired Power Plants



GT2021-58865

Sandeep Pidaparti, Ph.D.NETL Support Contractor



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Outline



- Introduction
- Plant Configurations
- Optimization Variables
- Optimization Approach
- Optimized Plants with Carbon Capture and Storage (CCS) (results)
- Optimized Plants without CCS (results)
- Summary and Conclusions
- Follow-on Work



Introduction



Motivation

- Most of the supercritical carbon dioxide (sCO₂) systems analysis studies in literature focused on efficiency-based optimization or dealt with manual economic optimization
 - Commercialization is driven by economics
 - Complexity of optimization increases with number of design variables

Background

- Recompression cycle (RC) is the most widely investigated configuration
 - Best suited for near constant temperature heat sources
 - Other cycle configurations such as partial cooling cycle (PCC) can be attractive option for heat sources that require a larger window of heat addition (e.g., concentrated solar power)

Objective

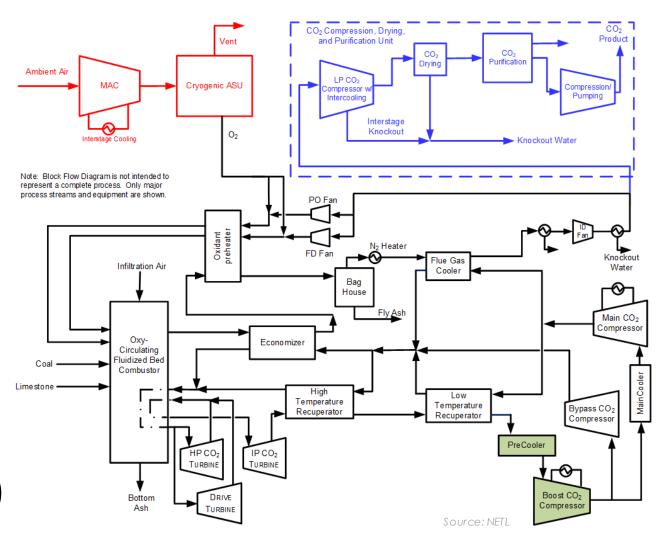
- Develop optimized indirect sCO₂ coal-fired power plant designs to minimize cost of electricity (COE), both with and without CCS
 - Determine optimal power cycle configuration for coal-fired power generation



Plant Configurations



- Coal-fired sCO₂ plants with CCS
 - Oxy-fired, atmospheric pressure circulating fluid bed (CFB) burning Illinois No. 6 coal
 - CO₂ captured using an autorefrigerated CO₂ purification unit (CPU)
 - Plants located at a generic Midwest ISO site
 - 15°C dry bulb temperature
 - 60% relative humidity
- Four power cycle configurations explored
 - RC without reheat (RC wo Reheat)
 - RC with reheat (RC w Reheat)
 - PCC without reheat (PCC wo Reheat)
 - PCC with reheat (PCC w Reheat)

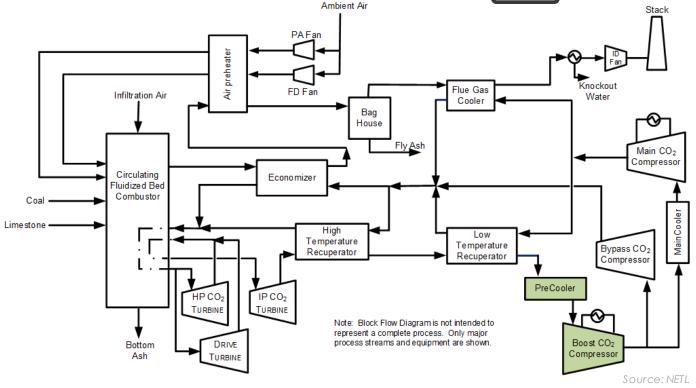




Plant Configurations (cont'd)

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- Coal-fired sCO₂ plants without CCS
 - Air-fired, atmospheric pressure CFB burning Illinois No. 6 coal
 - No ASU, CPU, N₂ heater, and flue gas recirculation
- Design constraints
 - Net power output = 650 MWe
 - 85% capacity factor
 - All the coolers and intercoolers have same CO₂ outlet temperature
 - Pressure ratios equal for all turbomachinery stages



Section	Parameter	Value
Turbines	Isentropic efficiency	92.7%
	Stages	2
Main and boost compressors	Intercooling stages	1
	Isentropic efficiency	85.0%
Dynama compressor	Stages (No intercooling)	1
Bypass compressor	Isentropic efficiency	85.0%



Optimization Variables



- Optimization search space for non-reheat cases
 - 13 design variables for RC
 - 16 design variables for PCC
- Optimization search space for reheat cases
 - 15 design variables for RC
 - 18 design variables for PCC
- Search space is noisy

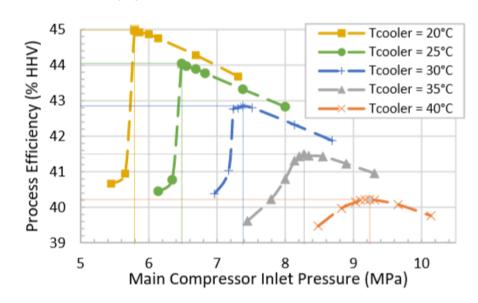
Design Variables	Minimum	Maximum
sCO ₂ cooler/intercooler outlet temperature, °C	20.0	35.0
Main heat turbine inlet temperature, °C	649.0	732.0
Reheat Turbine inlet temperature, °C	649.0	732.0
Compressor outlet pressure, MPa	27.6	44.8
Turbine outlet pressure, MPa	3.45	6.55
Boost compressor outlet pressure, MPa	5.52	8.27
High temperature heat recovery (HTR) cold end approach, °C	5.6	27.8
Low temperature heat recovery (LTR) cold end approach, °C	5.6	27.8
Economizer cold end approach temperature, °C	111.1	444.4
HTR total pressure drop, kPa	68.9	344.7
LTR total pressure drop, kPa	68.9	344.7
PC pressure drop, kPa	34.5	206.8
BCIC1 pressure drop, kPa	34.5	206.8
MC pressure drop, kPa	1.7	137.9
MCIC1 pressure drop, kPa	34.5	206.8
Primary heat tubing outer diameter, mm	19.1	57.1
Reheat tubing outer diameter, mm	38.1	63.5
Economizer tubing outer diameter, mm	38.1	63.5

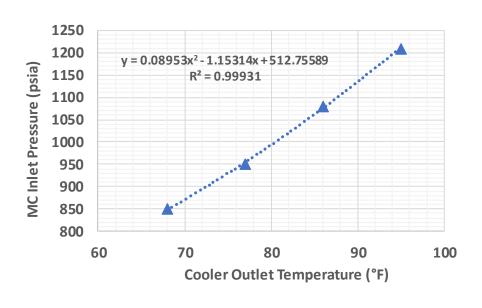


Optimization Variables (cont'd)



- From prior work, main compressor (MC) inlet pressure should be slightly
 higher than pseudo-critical/saturation pressure to reduce compression work
 - Maximizes cycle/plant efficiency
 - Optimization solvers took a long time to get to this search space
 - To reduce the run time, the MC inlet pressure is set based on cooler outlet temperature
 - This approach reduced the run time by over 50%



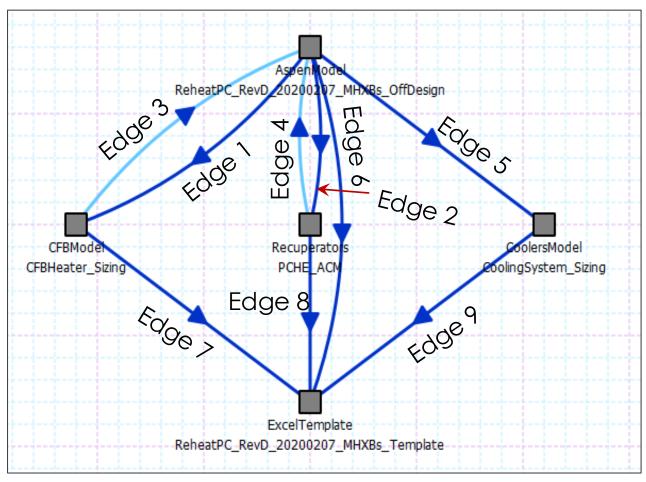




Optimization Approach



- Framework for Optimization, and Quantification of Uncertainty, and Surrogates (FOQUS) platform was selected for optimization
 - Part of NETL's Carbon Capture Simulation Initiative (CCSI) Toolset
 - Several built-in automated optimization algorithms available
- FOQUS model includes five nodes
 - Plant Aspen model (capture or noncapture version)
 - CFB model
 - Recuperators model
 - Adiabatic cooling system model
 - Performance/cost template

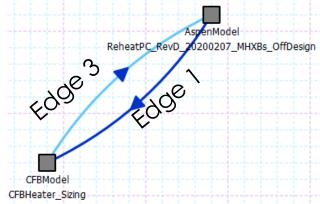


Node represents each model Edge represents interaction (data transfers) between each model





- Edge 1 (Data transfers)
 - For primary heat, reheat, and economizer sections
 - Tubing diameter
 - CO₂ flow rate
 - CO₂ inlet pressure & temperature
 - CO₂ outlet temperature
 - Flue gas inlet & outlet temperatures
- Edge 3 (Data transfers)
 - CO₂ pressure drop for primary heat, reheat, and economizer sections
 - Relative tolerance of 10⁻³ used as convergence criteria



DESIGN ASSUMPTIONS				
Primary heat tubing material	IN740H			
Reheat tubing material	IN740H			
Economizer tubing material	TP347HG			
Radiation section flue gas heat transfer coefficient A	200 W/m ² -K			
Convective section flue gas heat transfer coefficient A	75 W/m ² -K			
Waterwall tubing length ^A	65.6 m			
Inconel 740H tubing cost	40 \$/lb			
Stainless steelTP347HG tubing cost	7.3 \$/lb			
50% of material cost assumed for labor and installation				

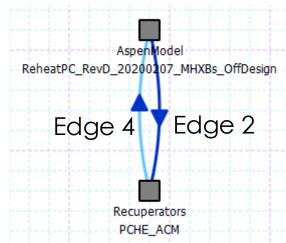
A From STEAMPRO software package for equivalent CFB boiler for steam Rankine plants





- Edge 2 (Data transfers)
 - For HTR and LTR
 - Hot and cold side mass flow rates
 - Hot and cold side inlet temperatures
 - Hot and cold side inlet pressures
 - Total pressure drop
 - Cold end temperature approach
- Edge 4 (Data transfers)
 - Hot and cold side pressure drops for HTR and LTR
 - Convergence criteria—relative tolerance of 10⁻³

¹Southall, David, Renaud Le Pierres, and Stephen John Dewson. "Design considerations for compact heat exchangers." In *Proceedings of ICAPP*, vol. 8, pp. 8-12. ICAPP, 2008.



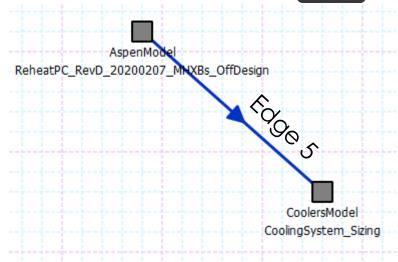
DESIGN ASSUMPTIONS				
Channelshape	Zig-Zag semi-circle			
Zig-Zag angle	High			
Pressure drop and heat transfer correlations, Mechanical Design	Heatric paper ¹			
Channel diameter (mm)	2			
Number of hot plates per cold plate	2			
Number of discrete points along the length	50			
Cost scaled with respect to mass ($C = 1,371.6 * M^{0.7842}$)				





- Edge 5 (Data transfers)
 - For cycle coolers (Pre-Cooler, MC) and intercoolers (Boost compressor and MC)
 - CO₂ mass flow rate
 - CO₂ inlet pressure and temperature
 - CO₂ outlet temperature
 - CO₂ pressure drop
 - Switch to set cycle architecture (recompression vs partial cooling)
 - Dry bulb temperature and relative humidity and air pressure
- Further details about performance modeling and economic analysis methodology can be found in associated paper (GT2021–58865)

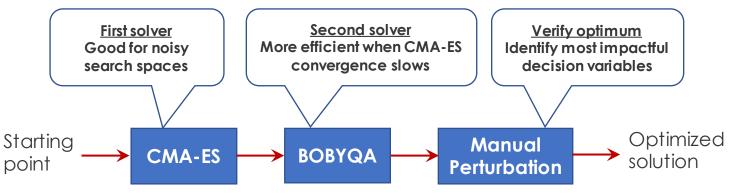
²C. White, S. Pidaparti, A. O'Connell and N. Weiland, "Cooling Technology Models for Indirect sCO₂ Cycles," National Energy Technology Laboratory, Pittsburgh, September 2019.



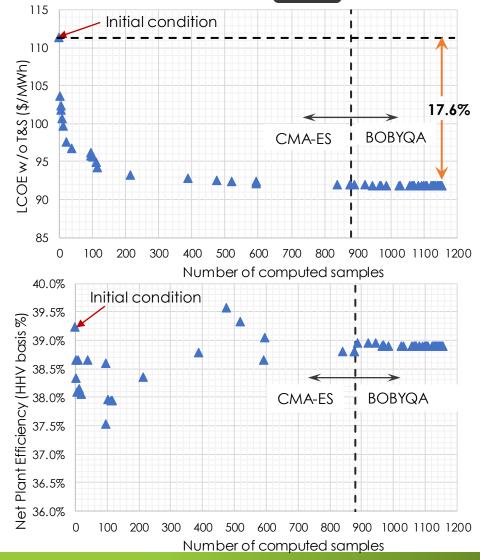
DESIGN ASSUMPTIONS				
Cooler module design and cost	Vendor (Güntner)			
Number of discrete points along the length	10			
CO ₂ side heat transfer coefficient and pressure drop calculations	Refer to technical documentation ²			
Air side heat transfer coefficient and pressure drop calculations	Refer to technical documentation ²			
Cost scaled with number of cooler bays ($C = 124,933 * N_{bays}$)				







- Objective function
 - Minimize levelized cost of electricity (LCOE) subject to constraints
 - Plant efficiency > 30%
- Close to 1200 samples computed
 - 85% of the samples converged
 - Run time ~ 96 hours
- Relative to the initial condition
 - 17.6% LCOE reduction
 - Minimal impact on plant efficiency





Optimized Plant Design Variables



Design Variables	RC wo Reheat	RC with Reheat	PCC wo Reheat	PCC with Reheat
sCO ₂ cooler/intercooler outlet temperature, °C	22.7	21.9	21.6	22.1
Main heat turbine inlet temperature, °C	706.0	661.0	712.0	666.0
Reheat turbine inlet temperature, °C	-	678.0	-	686.0
Compressor outlet pressure, MPa	28.8	37.7	35.5	43.9
Turbine outlet pressure, MPa	6.47	6.41	5.74	5.86
Boost compressor outlet pressure, MPa	-	-	6.08	6.16
HTR cold end approach, °C	11.5	13.8	17.8	16.6
.TR cold end approach, °C	9.6	10.9	10.1	9.5
Economizer cold end approach temperature, °C	222.0	278.0	195.0	232.0
HTR total pressure drop, kPa	174.4	237.4	165.4	160.0
.TR total pressure drop, kPa	164.8	162.3	100.7	146.2
PC pressure drop, kPa	-	-	102.7	118.6
BCIC1 pressure drop, kPa	-	-	89.6	113.1
MC pressure drop, kPa	9.0	7.2	6.9	8.3
MCIC1 pressure drop, kPa	116.5	137.7	82.7	181.3
Primary heat tubing outer diameter, mm	31.0	38.1	24.9	33.5
Reheat tubing outer diameter, mm	-	54.4	-	50.8
Economizer tubing outer diameter, mm	50.8	59.4	55.4	42.2
LCOE w/o T&S (Dec 2018\$)	90.9	89.9	93.5	91.8
Net Plant Efficiency (HHV basis)	38.9%	39.5%	37.8%	38.9%



Performance Summary

- B12B is a state-of-theart PC-fired supercritical steam Rankine plant with CCS
- Recompression cycles compared to partial cooling cycles
 - Higher recuperator (HTR, LTR) heat duties
 - Lower total cycle cooling duties due to higher thermal efficiencies



Parameter	B12B	RC wo Reheat	RC with Reheat	PCC wo Reheat	PCC with Reheat
Coal flow rate (kg/h)	273,628	221,498	219,992	228,214	219,761
HHV coal thermal input (MW _{th})	2,062	1,670	1,658	1,720	1,656
HHV boiler efficiency (%)	88.1	92.5	92.5	92.5	92.5
Net plant efficiency (HHV %)	31.5	38.9	39.5	37.8	38.9
Cycle specific power (kJ/kg)		174.4	206.2	211.4	238.9
sCO ₂ flow rate (kg/s)		4,685	3,985	3,887	3,392
	Power Gene	eration Summar	y (MW _e)		
Turbines gross power	770	1,074	1,095	1,067	1,062
Main compressor power	-	99	123	109	127
Boost compressor power	-	-	-	19	17
Bypass compressor power	-	146	139	106	95
Generator losses	-	12	13	13	12
Total auxiliaries	120	168	166	172	166
Net power plant output	650	650	655	650	644
	Power Cy	cle Heat Duties ((MW _{th})		
CFB thermal input	-	1,304	1,318	1,332	1,279
HTR duty	-	1,658	1,479	1,254	1,348
LTR duty	-	871	883	634	599
Main cooler duty	-	619	602	438	399
MC intercooler duty	-	96	98	90	94
Pre-cooler duty	-	-	-	193	187
BC intercooler duty	-	-	-	36	30



Economic Summary – Capital Costs

- sCO₂ plant costs lower than B12B
- Several sCO₂
 configuration
 differences from
 B12B
 - PC vs. CFB boilers
 - Oxy-combustion vs. post-combustion carbon capture
 - Cooling systems

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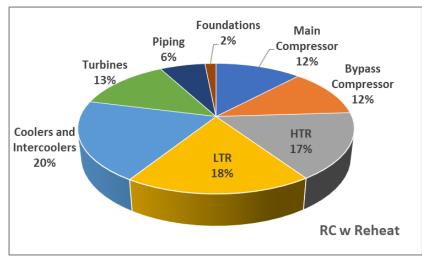
Cost Account Description	B12B	B12B RC RC wo Reheat with Reheat		PCC wo Reheat	PCC with Reheat		
Capital Costs (TPC, \$/1000)							
Coal & Sorbent Handling	\$89,404	\$66,069	\$65,788	\$67,313	\$65,744		
Coal & Sorbent Prep and Feed	\$25,272	\$35,647	\$35,488	\$36,351	\$35,464		
Feedwater & Miscellaneous BOP	\$157,933	\$23,735	\$23,677	\$24,418	\$23,581		
CFB/PC Boiler & Accessories	\$658,303	\$375,509	\$375,417	\$374,696	\$371,668		
Air Separation Unit	-	\$464,834	\$462,619	\$474,654	\$462,279		
Flue Gas Cleanup & Piping	\$970,432	\$29,906	\$30,640	\$28,990	\$28,985		
CO ₂ Removal & Compression	-	\$242,831	\$241,509	\$248,703	\$241,306		
FG Recycle, Ductwork & Stack	\$21,087	\$36,188	\$36,094	\$36,601	\$36,079		
sCO ₂ /steam Power Cycle	\$220,539	\$542,557	\$547,280	\$582,356	\$568,277		
Cooling Water System	\$94,597	\$30,713	\$30,574	\$31,329	\$30,553		
Ash & Spent Sorbent Handling	\$19,718	\$43,513	\$43,350	\$44,248	\$43,325		
Accessory Electric Plant	\$73,602	\$134,547	\$134,256	\$135,731	\$133,945		
Instrumentation & Control	\$24,742	\$37,672	\$37,630	\$37,795	\$37,620		
Improvement to Site	\$30,021	\$20,632	\$20,636	\$20,752	\$20,665		
Buildings & Structure	\$82,723	\$80,225	\$80,225	\$80,467	\$80,248		
Total Plant Cost	\$2,468,373	\$2,163,770	\$2,165,183	\$2,224,403	\$2,179,738		
Total Plant Cost (\$/kWe)	3,800	3,331	3,303	3,424	3,383		

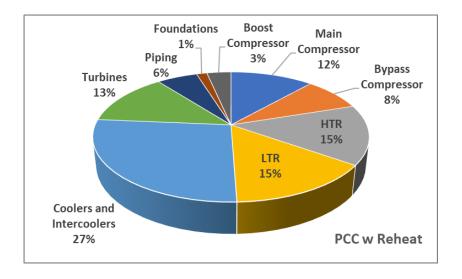


Economic Summary - Capital Costs (cont'd)

	RC wo Reheat	RC with Reheat	PCC wo Reheat	PCC with Reheat			
sCO ₂ Power Cycle Cost Breakdown (TPC, x\$1000)							
Main Compressor	\$51,543	\$65,813	\$52,058	\$65,689			
Bypass Compressor	\$68,372	\$65,600	\$49,917	\$47,553			
Boost Compressor	-	-	\$19,686	\$19,202			
High Temperature Recuperator	\$95,809	\$90,451	\$70,768	\$84,429			
Low Temperature Recuperator	\$101,189	\$101,033	\$79,187	\$83,277			
Coolers (Including intercoolers)	\$107,078	\$109,116	\$192,868	\$153,065			
Turbines	\$80,943	\$72,163	\$83,229	\$74,678			
System Piping	\$29,286	\$34,600	\$26,387	\$32,126			
System Foundations	\$8,337	\$8,502	\$8,256	\$8,257			
Total Sub-account Cost (TPC)	\$542,557	\$547,280	\$582,356	\$568,277			
Total Sub-account Cost (\$/kWe)	835	835	896	882			









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O&M Costs and LCOE Breakdown

- O&M and fuel costs lower than B12B due to higher plant efficiencies
- Order of increasing LCOE
 - Same as order of decreasing plant efficiency
 - RC with Reheat
 - RC wo Reheat
 - PCC with Reheat
 - PCC wo Reheat

	B12B	RC wo Reheat	RC with Reheat	PCC wo Reheat	PCC with Reheat		
Operating & Maintenance Costs (\$1,000/yr)							
Fixed O&M	78,065	68,086	68,126	69,745	68,526		
Variable O&M	67,775	61,488	61,238	63,413	61,305		
Fuel	116,691	94,460	93,818	97,324	93,719		
	LCOE	Breakdow	n (\$/MWh)				
Capital	51.0	44.6	44.2	45.8	45.3		
Fixed O&M	16.1	14.1	14.0	14.4	14.3		
Variable O&M	14.0	12.7	12.5	13.1	12.8		
Fuel	24.1	19.5	19.2	20.1	19.5		
LCOE (without T&S)	105.3	90.9	89.9	93.5	91.8		
T&S	8.9	7.4	7.3	7.6	7.4		
LCOE (with T&S)	114.3	98.3	97.2	101.1	99.3		



Stainless Steel CFB Tubing

- CFB primary heat and reheat tubing material changed for AltConfig1
 - Inconel 740H to stainless steel 304H
- With 304H CFB tube banks
 - Optimal main heat TIT ~610 °C
 - Optimal reheat TIT ~650 °C
 - Optimal CFB tube diameter ~3"
 - COE is <1% higher
 - Efficiency ~2 percentage points lower



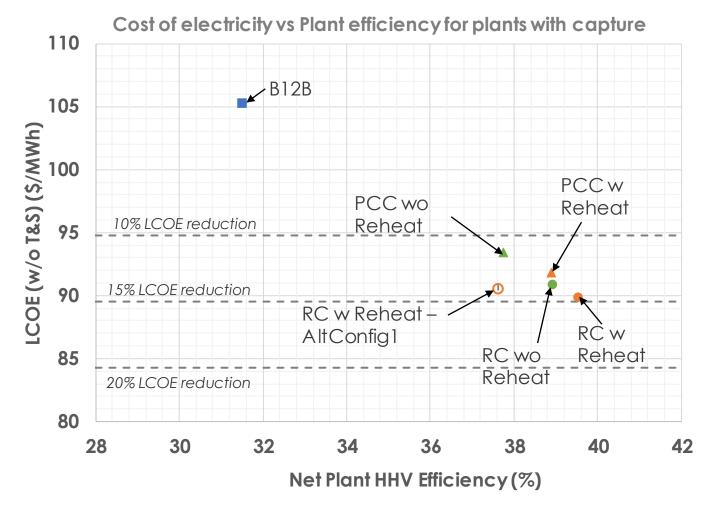
Design Variables	RC with Reheat	RC with Reheat - AltConfig1
sCO ₂ cooler/intercooler outlet temperature, °C	21.9	23.9
Main heat turbine inlet temperature, °C	661.0	611.0
Reheat turbine inlet temperature, °C	678.0	649.0
Compressor outlet pressure, MPa	37.7	35.2
Turbine outlet pressure, MPa	6.41	6.71
HTR cold end approach, °C	13.8	13.7
LTR cold end approach, °C	10.9	9.4
Economizer cold end approach temperature, °C	278.0	388.0
HTR total pressure drop, kPa	237.4	191.7
LTR total pressure drop, kPa	162.3	218.6
MC pressure drop, kPa	7.2	12.4
MCIC1 pressure drop, kPa	137.7	136.5
Primary heat tubing outer diameter, mm	38.1	73.2
Reheat tubing outer diameter, mm	54.4	73.2
Economizer tubing outer diameter, mm	59.4	72.9
LCOE w/o T&S (Dec 2018\$)	89.9	90.6
Net Plant Efficiency (HHV basis)	39.5%	37.6%



Summary of Key Results

- Recompression cycle with reheat (RC w Reheat) is the best performing configuration
 - Plant efficiency is 8% points higher than case B12B
 - LCOE w/o T&S is 14.6% lower than case B12B

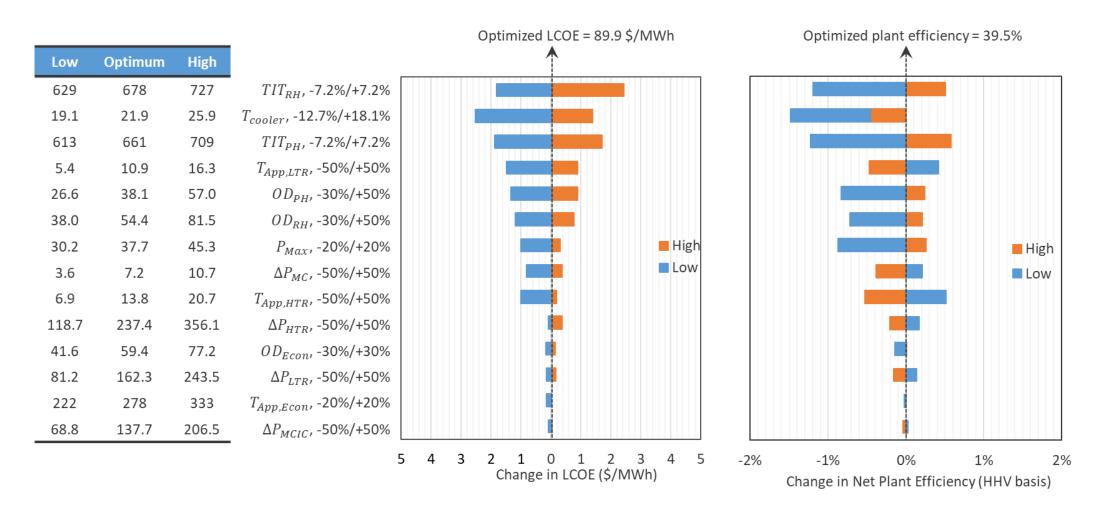






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RC With Reheat Sensitivity Analyses – Design Variables

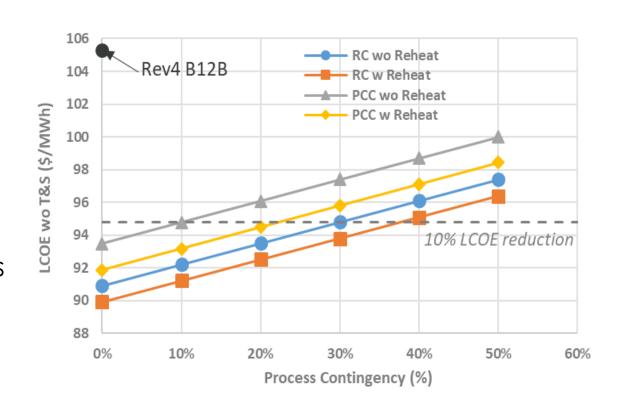




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RC With Reheat Sensitivity Analyses – Process Contingencies

- Capital costs for non-commercial components can be expected to be higher for first-of-a-kind (FOAK) plants
- Process contingencies are applied to non-commercial sCO₂ power cycle components
 - CFB, compressors, and turbines
 - 0% represent nth-of-a-kind (NOAK) plants
- If 40% process contingency is applied
 - RC w Reheat achieves about 10% lower LCOE than B12B case





Optimized Plant Design Variables

- Optimized designs without CCS compared to plants with CCS
 - Lower TITs
 - Higher cooler outlet temperatures
 - Lower maximum pressures
- Similar trends for LCOE, efficiency to that of plants with CCS

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Design Variables	RC wo Reheat	RC with Reheat	PCC wo Reheat	PCC with Reheat
sCO ₂ cooler/intercooler outlet temperature, °C	26.6	24.8	24.5	24.1
Main heat turbine inlet temperature, °C	678.0	649.0	694.0	654.0
Reheat turbine inlet temperature, °C	-	652.0	-	665.0
Compressor outlet pressure, MPa	33.1	33.6	33.1	41.0
Turbine outlet pressure, MPa	7.09	6.86	6.16	5.98
Boost compressor outlet pressure, MPa	-	-	6.52	6.45
HTR cold end approach, °C	21.9	19.8	24.5	21.6
LTR cold end approach, °C	9.3	11.1	11.3	11.3
Economizer cold end approach temperature, °C	411.0	429.0	278.0	382.0
HTR total pressure drop, kPa	153.1	248.8	191.0	217.2
LTR total pressure drop, kPa	171.7	185.9	174.4	160.6
PC pressure drop, kPa	-	-	194.4	140.0
BCIC1 pressure drop, kPa	-	-	101.3	140.1
MC pressure drop, kPa	20.7	16.8	12.4	12.4
MCIC1 pressure drop, kPa	174.4	174.4	175.8	171.0
Primary heat tubing outer diameter, mm	24.6	38.0	25.4	32.5
Reheat tubing outer diameter, mm	-	63.4	-	54.4
Economizer tubing outer diameter, mm	62.5	51.1	55.9	50.5
LCOE (Dec 2018\$)	60.2	59.9	61.8	61.1
Net Plant Efficiency (HHV basis)	44.1%	45.0%	43.5%	45.0%



Recompression Cycle With Reheat - Alternate Constraints



- RC w Reheat reoptimized with alternate constraints
 - AltConfig1: Maximize efficiency at LCOE parity with B12A
 - B12A is a state-of-the-art pulv erized coal (PC)-fired supercritical steam Rankine plant without CCS
 - AltConfig2: Minimize LCOE at plant efficiency of 50%
- Higher efficiency driven by
 - Higher TITs
 - Lower cooler outlet temperatures
 - Tighter recuperator approach temperatures
- Resulting total plant cost increases by 20% (for AltConfig1) and 29% (for AltConfig2)

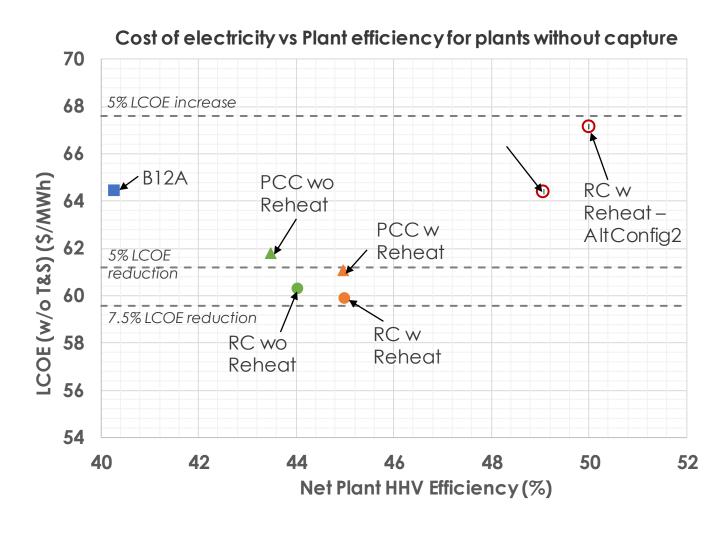
Design Variables	RC with Reheat	AltConfig1	AltConfig2
sCO ₂ cooler/intercooler outlet temperature, °C	24.8	19.9	19.0
Main heat turbine inlet temperature, °C	649.0	687.0	720.0
Reheat turbine inlet temperature, °C	652.0	709.0	710.0
Compressor outlet pressure, MPa	33.6	36.2	34.5
Turbine outlet pressure, MPa	6.86	6.07	5.88
HTR cold end approach, °C	19.8	10.3	6.4
LTR cold end approach, °C	11.1	9.0	8.9
Economizer cold end approach temperature, °C	429.0	435.0	443.0
HTR total pressure drop, kPa	248.8	223.4	108.9
LTR total pressure drop, kPa	185.9	107.6	122.7
MC pressure drop, kPa	16.8	3.4	2.8
MCIC1 pressure drop, kPa	174.4	165.5	120.0
Primary heat tubing outer diameter, mm	38.0	50.8	38.1
Reheat tubing outer diameter, mm	63.4	58.4	72.4
Economizer tubing outer diameter, mm	51.1	72.4	58.4
LCOE w/o T&S (Dec 2018\$)	59.9	64.4	67.2
Net Plant Efficiency (HHV basis)	45.0%	49.1%	50.0%



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Summary of Key Results

- RC w Reheat is the best performing configuration both in terms of plant efficiency and LCOE
 - Plant efficiency is 4.7% points higher than case B12A
 - LCOE w/o T&S is 7% lower than case B12A
- RC w Reheat achieves
 - 49.1% plant efficiency and LCOE parity with B12A case (AltConfig1)
 - 50% plant efficiency and LCOE 4.3% higher than B12A case (AltConfig2)





Summary and Conclusions



- FOQUS platform successfully used for economic optimization of oxy-fired CFB (with CCS) and air-fired CFB (without CCS) coupled to indirect sCO₂ power cycles
 - Using automated optimization solvers to minimize LCOE with respect to 13–18 plant design variables
- sCO₂ plants with CCS compared to a state-of-the-art PC-fired supercritical steam Rankine plant with CCS
 - 6.3–8.0 percentages points higher plant efficiency
 - 11.2–14.6% lower LCOE
- Optimum TITs for the investigated cases range 650–715°C
 - Requires use of nickel alloys and smaller tube diameters to keep the CFB costs low
 - Optimum tube diameters range 1.0–2.25"
 - Main heat section will require smaller tube diameters due to higher operating pressures



Summary and Conclusions (cont'd)



- Switching CFB tubing material from Inconel 740H to stainless steel 304H resulted in similar LCOE values, but ~2 percentage points lower efficiency
 - Lower optimum TITs (610–650 °C)
 - Optimum tube diameters range 2.5–3.0"
- sCO₂ plants without CCS compared to a state-of-the-art PC-fired supercritical steam Rankine plant without CCS
 - 3.2–4.7 percentages points higher plant efficiency
 - 4–7% lower LCOE
 - Can achieve LCOE parity with 8.8 percentage points higher plant efficiency
 - 18% reduction in CO₂ emissions
- Overall Impact: Improves economics and commercialization potential for sCO₂ power cycles
 - Results also applicable to nuclear and concentrated solar sCO₂ plants



Follow-On Work



- Optimize sCO₂ plant designs for different plant site conditions
 - Results presented under GT2021-58867 paper
- Optimize sCO₂ plant designs as a function of different plant sizes
 - Plant sizes ranging 50–650 MWe considered
- Optimize sCO₂ plant designs with coal and biomass co-firing to achieve net-zero or possibly net-negative CO₂ emissions



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Questions/ Comments

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